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Head Position Control and Target Localization Performance in Changing Gravito-Inertial Field

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Summary

A subject seated in a modern vehicle (i.e., aircraft) and performing motor tasks may be submitted to inertial forces (Coriolis and centrifugal forces). These forces are sources of spatial disorientation, leading to perturbations of sensori-motor behaviour. The coding of the position of the head, which carries visual and vestibular sensors, is of particular interest with regards to this problem. We have investigated the influence of the position of the head on the accuracy of pointing movements towards visual memorized targets performed in a modified gravito-inertial field in 10 subjects seated 70cm off-centre on a platform rotating at 120°/s. Subjects' head was either strongly immobilized in a vertical position (aligned with gravity vector) or completely free to move. Subjects were required to point as accurately as possible flashed visual targets presented in total darkness, before (PRE-rotation), during (PER-rotation) and after rotation of the platform (POST-rotation). Position of the head in the head free condition was recorded with an electromagnetic movement sensor (Polhemus Fastrack), whereas pointing accuracy as well as kinematics of the movements were recorded with an infrared position sensor device (Hamamatsu Motion Monitoring System).

Whatever the position of the head (head free or head restrained), rotation of the platform induced errors in pointing towards flashed visual targets in the direction of the new imposed forces (to the right in our experiment). However, the errors were greater when the subject's head was free to move than when maintained in a vertical position. Results obtained in the head free condition show a strong correlation between the angular position of the head during rotation and the increased errors in pointing movements.

Our data demonstrate that a change in the position of the head during rotation of the platform may have a strong effect on the accuracy of goal-directed behaviours. Reaching at a visual target requires transformation of visual information about target position with respect to the line of sight, into a frame of reference suitable for the planning of hand movement (body-centred reference frame). Our data suggest that coding of the position of the head during centrifugation may be inaccurate, leading to errors in localizing the real position of the presented target relative to the body. Our experiment confirms that modification of the position of the head during centrifugation may be a source of disorientation. It seems that fixation of the head in a given position may reduce the emergence of spatial disorientation. Moreover, recent data obtained in our laboratory suggest that peripheral visual information may help subjects to stabilize their head in a given position and reduce target localization errors.

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Introduction

Under normal terrestrial conditions, the force of earth gravity accelerates object, including us, down toward the surface (center) of the Earth. With experience, the brain establishes relationships between gravity, joint torques, and movements and thus integrate gravitational effect into internal dynamic models (Shadmer and Mussa-Ivaldi, 1994). As a consequence, orientation and sensory motor control mechanisms are normally dynamically tuned to this constant background acceleration level (Lackner and Dizio, 2000). The existence of such a calibration is usually 'perceptually transparent' to us so that we are not aware of the sensory and motor accommodations (motor commands have to continuously include an antigravitational component) that we make in relation to gravity. This calibration allows subjects to perform goal-directed behaviors with considerable accuracy in a variety of conditions (Atkeson and Hollerbach, 1985; Papaxanthis et al. 1998). For instance, Papaxanthis et al. (1998) asked their subjects to perform vertical arm pointing movements in two directions (upwards and downwards). Their results suggested different planning processes, for movements with and against gravity and indicated that gravitational force influences the processes controlling movement execution. However, when gravity is not the only force acting on individuals (for instance a subject seated in a car taking a bend), new inertial forces, that are the Coriolis and centrifugal forces, may represent a potential source of perturbation of goal-directed behaviors (Bourdin et al., 2001; Lackner and Dizio, 1998). In such conditions, subjects have to integrate these new inertial conditions to act. If not the case, goal directed behaviors may become less accurate than usually. For instance, a recent study showed that no complete motor adaptation[1] to the perturbations created by centrifugal and transient Coriolis forces may occur if visual feedback about reaching accuracy is denied (Bourdin et al, 2001). This study confirmed the predominant role of the vision on the ability to adapt to modification of the gravito-inertial field.

However, sources of errors in pointing movements performed in modified background force level remain largely unclear. Several explanations have been proposed in literature, as already mentioned by Bock et al. (1996). Clearly, perceptual as well as motor errors have been proposed to encounter the results, these sources of errors being not mutually exclusive. Perceptual errors include the possible mislocalization of the visually presented targets, as well as the possible altered coding of the limb position provided through proprioception. Motor errors include the direct mechanical effect of the gravitoinertial vector as well as the existence of an inappropriate motor commands to the background force level. These two types of errors were also investigated by Watt (1997) in a study analyzing accuracy of pointing movements towards memorized targets during prolonged microgravity. Watt hypothesized that the errors made when pointing actively at memorized targets during microgravity may be due to (a) a loss of an "internal spatial map", leading to not knowing where the arm was pointed, (b) a loss of an "external spatial map" leading to not knowing where the target was. His main objective was to determine the relative contribution of each of these potential sources of errors. Watt concluded his study in rejecting the hypothesis of a shift of the internal spatial map. According to him, inaccuracy in goal-directed movements towards memorized targets performed in microgravity was mainly due to uncertainty as to target location.

Our study is mainly concerns with the question of the perceptual errors and their consequences on the accuracy of pointing performances in modified background force level. One particular point, neglected in previous experiments performed in modified background force level, is the influence of head position on the accuracy of goal-directed behaviors. Head is the support of visual receptors as well as the vestibular apparatus, suggesting that head status is of particular importance in planification and execution of goal-directed movements performed in a modified background force level. Many experiments, performed in normo-gravity field, have shown that reaching at a visual target requires transformation of visual information about target position with respect to the line of sight, into a frame of reference suitable for the planning of hand movement, i.e. centered on the head, the trunk, the shoulder or the hand (body-centered reference frames) (Jeannerod, 1988; Blouin et al., 1993). The mechanism controlling egocentric visual localization and orientation is determined by inputs from the body-referenced mechanism (Retinal local sign information, extraretinal eye position information, extraretinal head orientation information) and from the visual field. Then, accurate coding of head posture seems an essential prerequisite to accuracy of goal-directed

[1] A remarkable and well-studied ability of the human brain is that of adapting the execution of limb movements to physical changes in operating conditions such as those that naturally occur during exposure to altered mechanical environments (Dizio and Lackner, 1995; Goodbody and Wolpert, 1998; Shadmer and Mussa-Ivaldi, 1994). This process is known as motor adaptation.

movements, in the sense that signals related to head position might be a cue for monitoring target position. According to this hypothesis, Biguer et al. (1984) compared the accuracy of hand pointing movements in a situation where the head was fixed and in a situation where it was free to move. Their results showed that the errors in pointing towards targets were considerably reduced for all targets in the head-free condition, especially for more eccentric targets.

In modified background force level, position of the head is submitted, as well as the other limbs, to new inertial forces, leading to possible changes in its position during a centrifugation protocol. In such dynamical condition, one of the prerequisite for the subjects to be accurate in pointing towards memorized targets is to precisely code the new head position relative to the body. In total darkness, vestibular cues as well neck afferents may play a crucial role in the coding of head position and then in the performance of goal-directed behaviors. The vestibular system includes two types of sensors: the semicircular canals and the otolith organs. The semicircular canals behave as integrating angular accelerometers measuring head angular velocity. The otolith organs provide information about head orientation with respect to the gravitoinertial force vector; under static conditions, this corresponds to head orientation vis a vis gravity. Proprioceptive neck afferents signals also play a major role in determining head position relative to the trunk.

However, accuracy in the proprioceptive coding of limb position (the head could be considered as a limb) has been questioned in gravitoinertial force field (Worringham and Stelmach, 1985). Indeed, these authors have suggested that the proprioceptive coding of limb position was less accurate in hypergravity (or micro-gravity) than in normo-gravity. For instance, under terrestrial conditions, head orientation in relation to the gravitoinertial resultant modulates muscle spindle sensitivity through otolith spinal mechanisms acting on the anti-gravity musculature of the body (Wilson and Melvill Jones, 1979). Moreover, results obtained by Bourdin et al. (2001) tended to show that proprioceptive signals on limb position can not lead to complete motor adaptation to modified background force level, and that vision was necessary for retrieving a high level of accuracy. This suggests that coding of head position during exposition to increased background force level could be less accurate than in normo-gravity condition. This type of sensory distortion may be a source of errors in pointing movements to memorized targets observed in previous experiments performed in modified background force level (Bourdin et al., 2001), because under these conditions the subject's body can serve as the coordinate system in which the movement is planned (Soechting and Flanders, 1989).

The main purpose of this study is to analyze the influence of head position on the accuracy of goal-directed movements performed in modified background force level. In a second level of analysis, we will be able to question the accuracy of head position coding in modified background force level and its relationships with motor performance.

Materials and Methods

Participants

10 right-handed subjects, aged from 18 to 35 (mean age = 23) took part in the experiment. None of the subjects had a history of vestibular abnormalities or other neurological disorders. All participants were unaware of the purpose of the experiment, and gave their informed consent prior to the beginning of the experiment.

Task and apparatus

A schematic representation of the experimental set-up is shown in figure 1. Subjects were comfortably seated on a rotating platform at 70 cm from the right of the axis of rotation. Tests were conducted with the platform either stationary or rotating counter-clockwise around its vertical axis at constant velocity (constant angular velocity of 120°/s). During rotation of the platform, subjects were submitted to a modification of the gravitoinertial vector (modification in amplitude and orientation). The resulting gravitoinertial force (Pythagorean sum of gravitation and centrifugal force) was 1.05g at subject's position. The gravitoinertial vector was inclined at 17.38°. A four-point safety belts was used to prevent body movement relative to the chair during the experiment and particularly during the rotation of the platform.

Seated subjects were facing a pointing table equipped with three red Light Emitting Diodes (LEDs) serving as targets to be pointed to. These three LEDs were positioned on a half circle, 30 cm radius centered on the subject's hand. A radial rather than linear disposition of the LEDs was chosen in order that the subjects could execute nearly the same movement amplitude from the body axis to every target. From the subjects' viewpoint, the targets were at 20° to the left (Left Target), 20° to the right (Right Target) and centered on the sagittal plane of the subject (Central Target). The targets were recovered with Plexiglas to suppress all tactile information on their position.

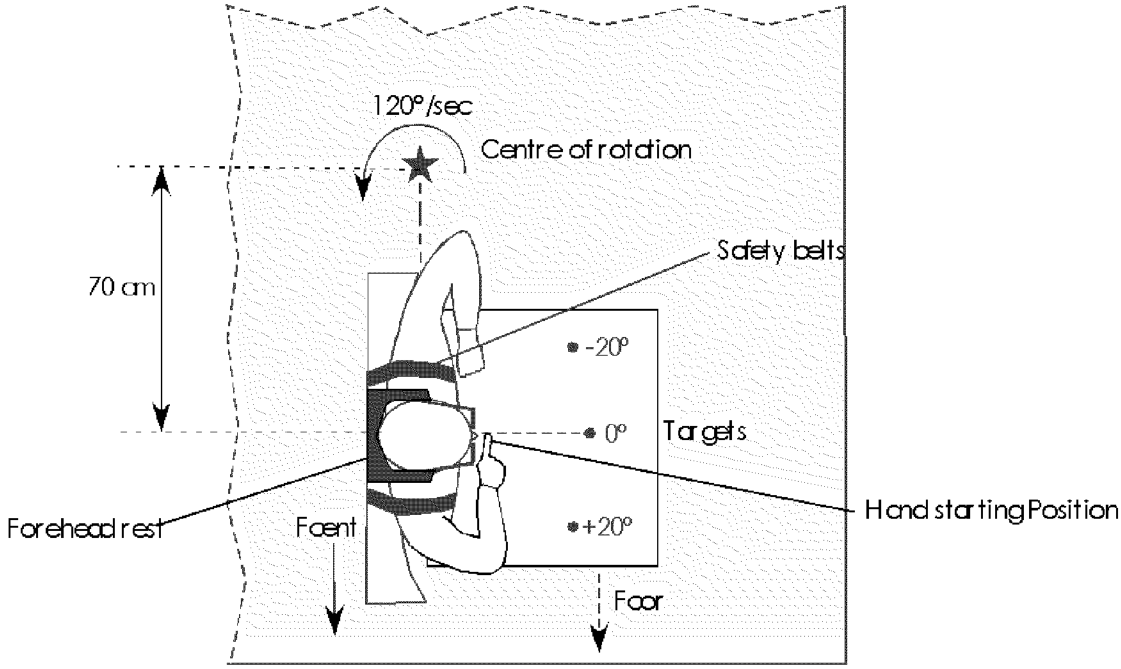

Figure 1. Schematic representation of the experimental set-up used in the experiment. Direction of the centrifugal force (Fcent) and of the Coriolis force (Fcor) during rotation of the platform are represented. Forehead rest was used to prevent any movement of the head during the HR session and safety belts prevented any movement of the trunk during both experimental sessions.

Procedures

Subjects were instructed to point with their preferred hand towards flashed visual targets (200 msec.), as accurately as possible. No time instruction was given to the subjects to allow maximum accuracy in the pointing task. Each subject participated in two experimental sessions. The first session was performed with the head fixed in a vertical position (vertical axis of the head aligned with the vertical axis determined by the gravity) (Head-Restrained condition, HR), whereas the second session was performed with the subject's head free to move (Head-Unrestrained condition, HU). In the HR condition, the trunk and head axes were kept closely aligned, whereas they were dissociable in the HU condition. In HR condition, the subject's head was stabilized in the natural upright position for looking straight-ahead by means of two rigid posts, covered with hard rubber, which pressed very firmly against the forehead. This forehead rest was designed to suppress the possibility of head movement about the three axis of rotation. At the start of the HR condition, position of the subject's head was regulated so that central target was exactly aligned on the sagittal plane (at the objective straight ahead, body midsagittal), so that the central target coincides with the cyclopean eye.

During HU condition, no instruction was given to the subjects concerning their head position. However, they were recommended no to produce fast movements of the head during rotation to prevent motion sickness.Each experimental session was divided into three blocks of 45 trials (15 trials for each targets), for a total of 135 trials. The three blocks were : (a) pre-rotation (PRE, no rotation of the platform), (b) per-rotation of the platform (PER) and (c) post-rotation (POST, no rotation of the platform). Subjects performed all

conditions in a complete darkened room and wore soldered glasses to be sure that no visual information (except the flashed target) was available. Both the onset and the offset of the platform's rotation produced a rotatory nystagmus. To eliminate its undesirable effect, which lasted a few seconds, the pointing movements in PER and POST condition started 1 minute after the end of the acceleration or deceleration phase. Order of the sessions was counterbalanced between subjects so that some subjects performed the HR session in first and the HU session in second and vice-versa. A few days separated each session. An experimental session lasted 1 hour in all.

Position in space of the head during the HU condition was recorded along three axes of rotation using a Fastrak (Polhemus) system. The Fastrack sensor was fixed on a low-weight helmet secured to the subject's head. The Fastrack emitting source was placed 50 cm beside the subject. These data were sampled at 120 Hz. Pointing movements were recorded with an infrared position sensor device at a sampling frequency of 200 Hz (Hamamatsu Motion Monitoring System). The monitoring system consisted of a matrix made of small infrared-emitting diodes positioned on the right index fingertip and an infrared-sensitive camera fixed perpendicularly above the table.

Data analysis

Angular errors (errors in direction) were computed by subtracting the target angle from the angle of the actual movement endpoint. Errors to the right of the target (in the sense of the inertial forces) were given a negative sign, whereas errors to the left (opposite to the direction of the inertial forces) were given a positive sign. Moreover, to overcome systematic errors in the pointing movements, we calculated normalized angular errors by subtracting the mean errors in direction made in PRE for each subject from those made in all conditions (PRE, PER, POST).

We were also interested in the kinematics of the pointing movements performed during the experiment. We analyzed movement time, as well as amplitude and time to peak velocity. Movement onset was defined as the time at which the tangential velocity reached 2.5 cm/s. Similarly, the first point in time that the velocity dropped under 2.5 cm/s was considered as the end of the movement.

Analysis of the head position during the experiment was based on two main angles that were computed as dependent variables. Roll angle was defined as the angle of the longitudinal head axis with the earth vertical, taken positive for right-ear-down rotations and negative for left-ear-down. Yaw angle was defined as the angle of the sagittal head axis with the earth sagittal plane, taken positive for head rotated to the left and negative for head rotated to the right. Pitch angles were not included in the analysis because preliminary analysis showed that rotation of the platform did not induce shift in the head position in pitch.

All the data concerning hand movements were submitted to 2 Head postures (Head Unrestrained and Head Restrained) x 3 Rotations (PRE-rotation, PER-rotation and POST-rotation) x 3 Targets (Right, Central and Left targets) analyses of variance (ANOVA) with repeated measures on all factors. Data on head position in HU condition were submitted to 3 Rotations (PRE-rotation, PER-rotation and POST-rotation) x 3 Targets (Right, Central and Left targets) analyses of variance (ANOVA) with repeated measures on all factors. Post-hoc analyses used the Newman-Keul's test.

Results

Analysis of Pointing movements

Normalized angular errors

Analysis of variance for normalized angular errors revealed a significant main effect of Rotation ($F(2,18)=18{,}98$; $p<.001$), and a significant interaction Head x Rotation ($F(2,18)=6{,}56$; $p<.01$). Our results showed that, whatever head position, normalized angular errors in pointing movements towards memorized targets were directly dependent on the condition of rotation of the platform, that is on the presence of new inertial forces. Indeed, with the platform in rotation, subjects made larger angular errors (4.73°) than when the platform was stationary (respectively, O° and –0.17° for PRE and POST conditions). Subjects pointed to the right of the presented targets during rotation of the platform, that is in the direction of the new inertial forces. This results confirms previous results obtained by Bourdin et al. (2001) on the influence of centrifugal and Coriolis forces on the accuracy of pointing movements made in complete darkness.

As illustrated in figure 2, the accuracy of pointing movements during rotation (PER-rotation) of the platform was significantly influenced by head position, whereas no significant effect of head position was found in PRE and POST-rotation. When subjects' head was free (HU condition) during rotation of the platform, subjects made greater angular errors (5.65° to the right of the targets) than when their head was fixed in a vertical position aligned with the trunk (HR condition, 3.82°) ($p<.001$).

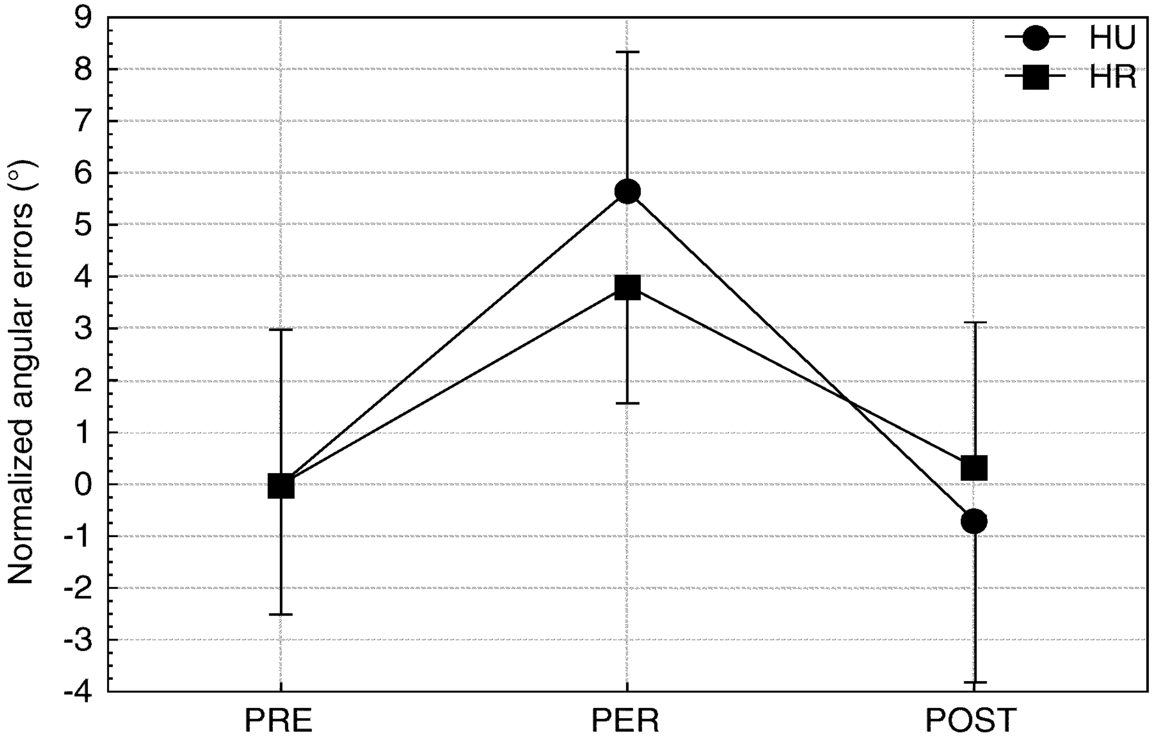

Figure 2. Mean and standard deviations of the normalized angular errors in function of the condition of Rotation and of Head Position. HU represents the session performed with the head free, whereas HR represents the session performed with the head fixed and kept aligned with the trunk during the experiment.

Movement time

The ANOVA revealed that rotation of the platform as well as position of the head did not significantly influence movement time when pointing to memorized targets. Whatever the head position, and whatever the gravitational condition, subjects performed hand movements within the same movement time (780 msec in average).

Amplitude of peak velocity

As for movement time, no significant effect of rotation and position of the head was found on the amplitude of peak velocity ($p>.05$). In average, amplitude of peak velocity was about 91 cm/sec whatever the head position or the amplitude and orientation of the gravitoinertial vector.

Time to peak velocity

The statistical analysis showed no main effect of rotation nor head position (global mean: 303 msec) on the moment of occurrence of the peak velocity ($p>.05$) confirming that the kinematic structure of the pointing movement was not influenced by rotation of the platform or by head position.

Our results suggest that having the head fixed and kept aligned with the trunk was of advantage for accuracy of pointing movements performed in such inertial conditions, without leading to modification of the kinematic features of the movements. Mechanical and inertial constraints on the moving limb being identical whatever head position during rotation of the platform, we hypothesize that normalized angular errors

observed in the HU condition may be related to the deviation of the head position during the rotation of the platform.

Analysis of head position

Normalized roll angle of the head

The ANOVA showed a main effect of Rotation on the normalized roll angle of the head ($F(2,18)=13,54$, $p<.001$). Subjects inclined their head towards the center of rotation of about 10 degrees during PER-rotation (-9.94°) comparative to the PRE and POST-rotation which were not significantly different from each other. The modification of the head position towards the center of rotation tended to align the longitudinal axis of the head with the new gravitational vector, even if this reorientation was not complete (head inclined at 10° whereas the gravitational vector was inclined at 17°).

Normalized yaw angle of the head

The ANOVA yielded a main effect of Rotation on the normalized yaw angle of the head ($F(2,18)=21,63$; $p<.001$). During rotation of the platform, subjects tended to rotate their head to the left, that is towards the center of rotation (in average, 8.6°), whereas centrifugal force was directed to the right, that is towards the outside of the platform. Position of the head in yaw in PRE and POST-rotation were not significantly different ($p>.05$).

Discussion

The main objective of our study was to analyze the influence of head position on the accuracy of pointing movements towards visual memorized targets performed in modified background force level.

Our results firstly confirm previous results obtained on pointing movements towards visual targets performed in modified background force level (Bourdin et al., 2001). It appears that, whatever head position, subjects made large angular errors in the direction of the inertial forces when pointing towards visual memorized targets. The amplitude of these errors was constant during the rotation of the platform. After rotation, subjects immediately retrieved a high level of accuracy, that is the same level of accuracy than during PRE-rotation. These results firstly confirm that rotation of the platform induces perturbations in the execution of goal-directed behaviors. Moreover, our data also confirm that no adaptation of the pointing movements occurred during the rotation of the platform in complete darkness. As suggested previously (Bourdin et al., 2001; Lackner and Dizio 1998), vision of the limb seems to be a essential prerequisite for such an adaptation.

The main result of this study is that amplitude of the angular errors made during rotation of the platform depends critically on the position of the head. Changes of the position of the head relative to the body systematically influence amplitude of angular errors when subjects pointing towards memorized targets in modified background force level. Our results suggest a strong relationships between head position and angular errors when inertial forces perturb limb movements. These results are different from those of Biguer et al. (1984) obtained in a normogravity field. These authors showed that accuracy of pointing movements was higher when subjects were able to move their head than when it was maintained aligned with the trunk. In contrary, our results showed that, in modified background force level, accuracy of pointing movements was greater when the head was maintained fixed and aligned with the vertical. Our abilities to localize objects in space, orient relative to them, move toward or away from them, and reach and manipulate them depend critically on receiving, processing, and integrating spatial information from gravity, the visual field, and the observer's own body. For instance, manually reaching to a visual object presented in total darkness requires the coding of the object position in relation to the body (Jeannerod, 1988). The basic coordinate system for such a task is the egocentric frame of reference, which allows the computation of the spatial position of visual objects with respect to the observer. In the visual input-motor output chain, these egocentric coordinate systems (e.g., head-centered, body-centered) are interposed (intermediate representations) between sensory input (encoded in retinal coordinates) and motor output, such as an arm reaching movement towards a visual object. These egocentric spatial coordinates are computed through the integration of inputs from multiple sensory sources (visual, proprioceptive-somatosensory, vestibular), entailing a coordinate transformation from sensory (retinotopic) to higher-order spatial egocentric and world-center representations or frames of reference. Because of this, accuracy of targeted movements was partly

dependent of the coding of head position which determined itself the spatial localization of the target. Our results showed a strong relationships between head position and amplitude of angular errors, suggesting that head position was probably not precisely coded in this particular inertial condition. This may confirm the hypothesis of an altered proprioceptive coding of limb position (and particularly of head position) suggested by previous authors (see Bock et al., 1996 for a review). Object localization in space in the absence of an external (visual, auditory, haptic) reference is known to involve a signal of head position in space derived from vestibular cues (Blouin et al., 1995) and from neck proprioceptive afferents. By considering the head as a limb, we could hypothesize that head position could be misperceived (because of the altered proprioceptive coding) leading to mislocalization of the presented targets. This suggests that the observed errors in our experiment were mainly due to this perceptive phenomenon. Our data also showed that rotation of the platform, as well as change in the position of the head did not influence the kinematic features of the pointing movements, confirming that the observed effects of rotation of the platform and of change of the position of the head on accuracy of goal-directed behaviors would have a perceptive component.

Finally, it is noteworthy that subjects made errors in performing the task with the head fixed in a vertical position. However, the errors were weaker when the subjects' head was fixed then it was free. Two hypotheses can be proposed to explain this result. Firstly, we propose that the altered proprioceptive coding of the head previously described could be responsible for the errors performed with the head fixed. As the head was kept vertical and aligned with the trunk, this perceptive distortion would have less provocative effects on the visual localization of the target and then on the accuracy of the movements. Secondly, we hypothesize that the inaccuracy of pointing movements performed during the rotation of the platform with the head fixed could reflect motor errors, in the sense of a non-adequate motor command sent to the effectors (Bock et al., 1996). Indeed, when required to point towards memorized visual targets during the rotation of the platform, subjects had to take into account the direct mechanical effect of the inertial forces on the moving limb. If not the case, the motor command could be inappropriate to the new gravitational force field, leading to inaccuracy in the execution of goal-directed movements. The existence of such motor errors had to be tested more clearly.

In conclusion, our results suggest that the observed errors in pointing movements towards memorized targets when orientation of the gravitational vector is modified may have an perceptive component. Our experiment confirms that modification of the position of the head during centrifugation may be a source of spatial disorientation. It seems plausible to propose that fixation of the head in a given position (to be defined) may reduce the emergence of spatial disorientation. Our data suggest that modification of the head position in such gravitational force field may have direct consequences on the accuracy of motor behavior when vision is precluded. For example, recent data obtained in our laboratory showed that peripheral visual information presented in total darkness during rotation of the platform induces a reorientation of the head in the direction of the visual information. On the basis of our experiment, we suggest that a peripheral visual information may allow to modulate the amplitude and the direction of the errors (depending on the orientation of the head) made in pointing movements. Specific directional effects of the head position has to be tested to confirm this hypothesis.

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